Evaluation of Unsupported Structural Exciters

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Biography

David Banaszak graduated from the University of Wisconsin with a B.S. degree in Electrical Engineering. He received a M.S. degree in Applied Statistics from Wright State University. Since 1971, he has worked for the Structures Division of the Flight Dynamics Directorate of the Air Force Research Laboratory as a project and instrumentation engineer. He is responsible for making acoustic, vibration and loads measurements for numerous Air Force test programs in the laboratory and the field.

Mike Fabian has worked as an electronics technician for the Air Force Research Laboratory since 1972. His areas of expertise are electrodynamics shakers and shaker control systems. Mike has an Associates degree in Electronic Engineering Technology from Youngstown State University.

Carlton Bowers teaches algebra and physics at Milton-Union High School in West Milton, OH. Carlton accomplished detailed measurements, required for this designed experiment, during the summer of 1996 as part of the Wright Connection program. Carlton has a B.S degree from John Hopkins University.

Abstract

Wright Laboratory is evaluating a new vibration calibration technique that allows one person to perform end-to-end calibrations of a structural dynamics measurement system including mounted transducers, signal conditioning and recorder. This new technique uses an unsupported structural exciter(USE). This technique stimulates structural measurement transducers, inside of structures, with a measurable acceleration level. If a transducer is mounted on a test structure, it is difficult to stimulate the transducer with a known physical input. A person must hold the exciter or attach a conventional vibration shaker to a structure. Two persons are required to calibrate, one at the transducer holding the exciter and one at the measurement system. Now one person can calibrate. Laboratory engineers conducted an experiment to evaluate a commercial off-the-shelf vibration paging system consisting of a master control unit and 8 individual exciters(pagers) to excite accelerometers mounted on structures. An accelerometer on the front of the structure measured the vibration input. This paper discusses the instrumentation and a completely randomized block design experiment consisting of three 2-level experimental factors: structural material, structural thickness and excitation mode. A blocking factor was each of the 8 different exciters(pagers) serial numbers. For each of the 64 combinations, a technician used a spectrum analyzer to record and compute the output amplitude, fundamental frequency and transfer function between the two accelerometers. This paper presents results from the experiments and describes the new technique.

Keywords

Calibration, vibration, structures, unsupported exciters, statistics, experimental design.

Background

This experiment validates new techniques utilized in AF Invention D00160(Reference 1). During this pilot experiment we investigated the amplitude and frequency of vibration levels using a prototype USE. The objective was to determine if there are significant differences in the amount of vibration excitation levels induced into different combinations of exciters, structural material and widths and exciter excitation modes. The experiment will help determine whether this new calibration concept gives repeatable or predictable vibration levels for different structure types.

Figure 1 shows the components of the J-Tech, Inc model 'XT' pager system which were used in the prototype USE(Reference 2). The pager system consists of a master control unit which sends an radio frequency signal to activate one of 8 vibration type pagers which are used for exciters in the prototype. Figure 2 shows a typical USE system with one exciter for testing acceleration on a thick Aluminum bar simulating a structure under test. Test structures are clamped in a vise that rests on a mouse pad to isolated the structure from table vibrations. An exciter is connected to the front side of the structure using tesa® 4970 double-sided PVC tape. A PCB® model 353B17 accelerometer(A1) on the back side of the structure simulated a typical accelerometer mounted inside an aircraft structure such as a aircraft wing. A PCB® model 353B17 accelerometer(A2) on the front side of the structure measured the vibration input.

The four structures tested are show in figure 3. The thin Aluminum weighed 31.8 grams and had dimensions of 14.00 x 7.54 x 0.11 cm. The thin wood weighed 21.4 grams and had dimensions of 35.03 x 2.78 x .30 cm. The thick wood weighed 364.9 grams and had dimensions of 49.86 x 5.54 x 1.92 cm. Lastly, the thick Aluminum weighed 481.2 grams and had dimensions of 17.50 x 8.02 x 1.32 cm. Each accelerometer weighed less than 5 grams and each exciter had a mass of between 53 and 54 grams.

Experimental Design

An experiment was designed to measure the amplitude and frequency and transfer function for two structural materials, two structure widths, eight exciters and 2 control modes to determine the feasibility of using the USE as an accelerometer calibrator. For this experiment the factors and levels (codes) were Material: Aluminum(1) or wood(2), width(or thickness): thin(1) or thick(2), controller excitation mode: 1 sine burst(1) or 16 sine burst(16), and exciter ID: (1-8). Selection of factors were difficult. Mass can also be considered a factor, but we assumed mass is roughly proportional to width.

The above four factors were selected to limit the number of measurements to 2x2x2x8=64 measurements for a randomized complete block design. The experimental units are the eight individual exciters. Vibration data from the two accelerometers were recorded on a four-channel spectra analyzer and a digital tape recorder for each of the 64 combinations of material, width, mode and exciter.

Each exciter is considered to be a block and transducer serial number(ID code 1 through 8) is a blocking factor. Each exciter may have significantly different excitation levels, but the level should remain constant from one structure type and support to another. Since we then have 1 measurement per block and treatment combination, we basically end up with a repeated measures design as described in reference 3 & 4. This is a special case of the randomized complete block design discussed in Chapter 10 of reference 5.

Other sources of variation include the structure dimensions, mass, the exciter support, attachment material of the exciter to the structure, the person doing the calibration, environmental factors such as temperature and humidity, transducer voltage excitation, the measuring equipment(voltmeters, oscilloscopes and spectrum analyzers), signal conditioners between the transducer and measuring equipment, calculators and computers required to perform necessary computations. All tests were at room temperatures. For this experiment the above variates are considered to be minor nuisance factors.

Each exciter was randomly assigned to a width, material and controller mode using a SAS® Institute,Inc. JMP® program described in reference 6. Table I incorporates the random order of the measurements. We purchased the exciters on two orders. Exciter 1 and 2 were purchased first and exciters 3-8 were purchased on a second order. The model will be a repeated measures design(randomized complete block design) with 8 blocks and 3 factors with two levels. The model is

$$y_{ijkl} = \mu + \tau_{ijk} + \theta_l + \varepsilon_{ijkl}$$

where τ_{ijk} are the treatment effects for Factor A=Material i=1,2, Factor B=Width j=1,2 and C=Mode k=1,2. θ_l is the lth block(exciter) l=1,2,3,....8. (Equation 7.1.1 in reference 5).

Initial Evaluations

Initial evaluations consisted of measuring the vibration amplitudes, using 1 accelerometer mounted on a random exciter from the paging system purchase from J-TECH incorporated. The exciter was tested initially on a foam pad. A sketch of the initial measurements will be made by observing the accelerometer signal with a Tektronix oscilloscope and an Oni-Soki Model CF-6400 spectrum analyzer are shown in figure 4. As shown in the sketch, the selected exciter had a sine shaped pulse of a duration of about 0.8 second. The frequency content showed a fundamental frequency at 148 hertz and a harmonic at a lower level. On the scope, we could also observe the High Frequency pulse initiated by the radio frequency(RF) signal sent from the master control unit to the exciter. The vibration measuring equipment(tape recorder and spectra analyzer) did not respond to this high frequency.

Instrumentation Setup

A block diagram of the data recording instrumentation used for this experiment, during the period of 2 July to 29 July 1996, is shown in figure 5. Each exciter was charged overnight. The accelerometers were PCB® model 353A17 accelerometers powered and amplified by PCB® Model 480D06 power units. PCB® instrumentation are described in reference 7. The analyzer was an Ono-Sokki model CF-6400 Fast Fourier Transform(FFT) analyzer described in reference 8. The tape recorder was a Metrum Model RSR 512 rotary storage recorder described in reference 9.

At the beginning of each test day, the accelerometer sensitivities were checked using a PCB® Model 394B06 1grms calibrator and the FFT analyzer by averaging 10 spectra of the accelerometer output signal. For the 13 daily checks, A1's sensitivity had a range of 10.007 to 10.175 mV/g and A2's sensitivity had a range of 9.540 to 9.704 mV/g. The daily variation was small, so for the entire test we use the initial value of 10.152 mV/g for A1 and 9.695 mV/g for A2 to calibrate the spectrum analyzer to read out gs directly for each of the 64 experiments.

A block diagram of the data playback instrumentation is shown in figure 6. The time history signal recorded on the Metrum tape recorded can be played back in analog format back into the spectrum analyzer. The signal can also be transferred in digital format to a Personal Computer using the techniques described in reference 10. For this paper we concentrated on analyzing data stored directly as spectra on the analyzer. Later, data on tape can be analyzed in more detail. Also, the tape recorder simulates a field test where we have transducers connect to a recorder and we require an end-to-end calibration of a accelerometer.

Test Procedure

The USE was configured for each combination of the four factor levels shown in Table I. For example for the first test listed, exciter ID 6 was mounted on the structure, the structural material used was thick wood in the vise and the excitation mode was one sine burst initiated by the master controller. The spectrum analyzer and recorder were turned on to record the data before initiation of the exciter vibration by turning on the master control unit. The output from the 2 accelerometer amplifiers were recorded as frequency spectra on the spectrum analyzer and recorded as time histories on tape at frequencies up to 5000 hertz.

The dual channel analyzer was set up to measure vibration amplitude (a1f0) in gs rms, fundamental frequency (f0) in hertz and transfer function at the fundamental frequency H(f0) between A1 and A2 for each of the 64 possible test conditions. The spectrum analyzer use A1 as a trigger signal to capture spectra for each vibration burst. For excitation mode 1 only 1 spectra was averaged and for excitation mode 16 all spectra were averaged. Average spectrum were saved on a MS-DOS compatible floppy disk in ASCII format for latter evaluation using EXCEL, SAS® or other analysis software.

Statistical Data Analysis

Table I shows the measurements obtained using the spectrum analyzer. The table includes measurements for the fundamental frequency f0(Hz), Vibration amplitude A1(fo) at the fundamental frequency, the transfer function H(fo) at the fundamental frequency and the frequency f1(Hz) and amplitude A1f1(ugs) of the next most significant sinusoidal component. Only the fundamental frequency was analyzed since it was the main component. As seen in the table, for the fundamental frequency, there is variation in frequency and amplitude, but the transfer function column stays close to one. It was decided to do some statistical analysis to help better analyze the results. Three analysis of variance(ANOVA) Tables were generated using a SAS® program to check for effectiveness of blocking, and test for interaction between factors.

Table IIa is the ANOVA table for considering the fundamental frequency as the response variable. The F-value of 106.78 for ID is much greater than 1 which implies that blocking is effective or exciter ID tends to effect the fundamental frequency. There appears to be insignificant interaction between the other factors and the only significant factor appears to be WIDTH.

Table IIb is the ANOVA table for considering the vibration amplitude(A1f0) at the fundamental frequency as the response variable. The F-value of 4.92 for ID is greater than 1 which implies that blocking is effective or exciter ID tends to effect the vibration amplitude. There appears to be significant interaction between material and width. Both material and width are significant factors. Mode and other interactions are insignificant.

Table IIc is the ANOVA table for considering the transfer function H(f0) at the fundamental frequency as the response variable. The F-value of .89 for ID is less than 1 which implies that blocking is not effective or ID does not tend to effect the transfer function. There appears to be no significant main factors but some interactions appear to be significant. These interactions are of low concern since from table I all transfer functions are within 10% of 1.00. This indicates that comparison calibration is indeed feasible.

Figures 7-9 are plots generated using the SAS® JMP® computer software to plot the measured data shown in table I. These plots confirm the results shown in the ANOVA tables. As explained in reference 6, the plots show a means diamond where the upper and lower points of the means diamond span a 95% confidence interval computed from the sample values for each factor level. The top and bottom of the quantile boxes represents the 75th and 25th quantiles. The 10th and 90th quantile are the lines above and below the box.

In figure 7, the frequency shows large variation for the different exciters and the most significant differences in frequency appears to be due to the width of the material. In figure 8, there appears to be a significant difference in vibration amplitude due to material and width. In figure 9, there appears to be no significant difference in transfer function due to any of the main factors.

Summary and Conclusion

The unsupported structural exciter works and is a feasible product for the calibration of accelerometers that are in inaccessible locations. Vibration frequency is significantly different for different serial numbers, and material widths. Vibration amplitudes varied significantly for different materials, widths and exciter IDs. Excitation mode was not a significant factor. The transfer function did not significantly change for different ID, material, width or mode. Hence it is reasonable to assume that a comparison calibration between an accelerometer near the exciter(A2) and an unknown accelerometer(A1) embedded in the structure will be reasonably accurate.

Since there is no currently know way to accomplish calibration of embedded transducers, this is a significant accomplishment. Future studies should be made in reducing the mass and size of the unsupported structural exciter and conducting designed experiments on some real life structures.

Acknowledgments

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Table I Experimental Design and Analyzer Measurements

Order	Pattern	ID	Material	Width	Mode	f0(Hz)	A1f0(gs)	H(f0)	f1(Hz)	A1f1(ugs)
1	6221	6	Wood	Thick	1	170.00	1.228	1.0010	340.00	44537
2	8122	8	Al	Thick	16	135.00	0.078	1.0030	268.75	285
3	8112	8	Al	Thin	16	133.75	0.078	0.9553	267.50	3815
4	1111	1	Al	Thin	1	153.75	0.380	0.9553	307.50	4835
5	6121	6	Al	Thick	1	181.25	0.160	0.9934	362.50	4610
6	5222	5	Wood	Thick	16	172.50	1.092	1.0090	346.25	90917
7	3221	3	Wood	Thick	1	175.00	0.902	1.0110	348.75	62705
8	7111	7	Al	Thin	1	163.75	0.417	0.9288	327.50	24684
9	8111	8	Al	Thin	1	136.25	0.153	0.9231	273.75	3723
10	6222	6	Wood	Thick	16	180.00	1.733	1.0070	360.00	26280
11	4222	4	Wood	Thick	16	177.50	1.390	1.0100	356.25	69588
12	4122	4	Al	Thick	16	177.50	0.123	1.0050	356.25	745
13	5122	5	Al	Thick	16	175.00	0.133	1.0050	348.75	5437
14	7211	7	Wood	Thin	1	171.25	4.527	0.9920	343.75	26740
15	1221	1	Wood	Thick	1	156.25	0.285	1.0300	311.25	5430
16	2111	2	Al	Thin	1	153.75	0.129	0.9144	308.75	40906
17	6112	6	Al	Thin	16	181.25	0.430	1.0140	362.50	14517
18	6212	6	Wood	Thin	16	171.25	5.381	0.9999	341.25	90482
19	8121	8	Al	Thick	1	131.25	0.072	1.0120	262.50	249
20	2222	2	Wood	Thick	16	148.75	0.233	0.9477	296.25	52476
21	5221	5	Wood	Thick	1	176.25	1.286	0.9882	352.50	54017
22	5211	5	Wood	Thin	1	173.75	4.363	1.0200	347.50	234052
23	7222	7	Wood	Thick	16	177.50	1.162	0.9945	355.00	54221
24	1121	1	Al	Thick	1	158.75	0.103	1.0050	317.50	421
25	2212	2	Wood	Thin	16	156.25	2.385	0.9747	311.25	16134
26	2122	2	Al	Thick	16	156.25	0.098	1.0040	313.75	1053
27	4211	4	Wood	Thin	1	175.00	4.671	0.9653	350.00	115617
28	1122	1	Al	Thick	16	158.75	0.104	1.0050	317.50	393
29	3211	3	Wood	Thin	1	168.75	3.451	1.0030	337.50	623
30	5112	5	Al	Thin	16	168.75	0.533	1.0670	338.75	103363
31	7212	7	Wood	Thin	16	171.25	6.930	1.0010	342.50	177390
32	3212	3	Wood	Thin	16	170.00	4.436	0.9849	338.75	334
33	4221	4	Wood	Thick	1	180.00	1.488	1.0030	360.00	58758
34	2221	2	Wood	Thick	1	156.25	0.289	1.0090	313.75	10950
35	1112	1	Al	Thin	16	148.75	0.161	1.0650	297.50	106472
36	2112	2	Al	Thin	16	136.25	0.250	1.0400	273.75	52523
37	7112	7	Al	Thin	16	176.25	0.408	1.0790	352.50	9058
38	3111	3	Al	Thin	1	176.25	0.531	0.9545	352.50	36341
39	7221	7	Wood	Thick	1	178.75	1.277	1.0090	356.25	59189
40	7121	7	Al	Thick	1	178.75	0.129	1.0060	357.50	8002
41	3222	3	Wood	Thick	16	177.50	1.045	0.9960	353.75	45266
42	8222	8	Wood	Thick	16	136.25	0.071	1.0270	271.25	1980
43	8221	8	Wood	Thick	1	132.50	0.064	1.0150	265.00	2964
44	2211	2	Wood	Thin	1	158.75	2.561	1.0090	317.50	11037
45	2121	2	Al	Thick	1	157.50	0.110	1.0060	315.00	1331
46	1211	1	Wood	Thin	1	157.50	2.288	1.0100	313.75	18998
47	6211	6	Wood	Thin	1	172.50	4.862	1.0030	345.00	305785
48	6122	6	Al	Thick	16	183.75	0.135	1.0010	367.50	5543
49	5111	5	Al	Thin	1	170.00	0.507	1.0730	338.75	448071
50	6111	6	Al	Thin	1	182.50	0.573	1.0480	366.25	17860
51	8212	8	Wood	Thin	16	136.25	1.319	0.9841	272.50	26571
52	7122	7	Al	Thick	16	178.75	0.129	0.9979	357.50	8288
53	4112	4	Al	Thin	16	171.25	0.246	1.0370	341.25	351752
54	8211	8	Wood	Thin	1	137.50	1.055	1.0350	275.00	23929
55	4121	4	Al	Thick	1	178.75	0.139	1.0000	357.50	7415
56	4212	4	Wood	Thin	16	167.50	7.547	1.0040	332.50	273908
57	3122	3	Al	Thick	16	176.25	0.122	0.9957	352.50	10269
58	1212	1	Wood	Thin	16	153.75	3.511	1.0050	307.50	53075
59	3121	3	Al	Thick	1	176.25	0.124	0.9988	352.50	6835
60	5212	5	Wood	Thin	16	168.75	5.974	0.9988	336.25	242680
61	5121	5	Al	Thick	1	176.25	0.131	1.0010	352.50	8046
62	3112	3	Al	Thin	16	171.25	0.580	1.0840	342.50	29496
63	1222	1	Wood	Thick	16	156.25	0.282	1.0100	312.50	3858
64	4111	4	Al	Thin	1	176.25	0.839	1.0350	352.50	26588

Table II ANOVA Tables for Frequency, Amplitude and Transfer Function

(a)Dependent Variable: Y1 f0=Fundamental Freq(Hz)

Source	DF	Sum of Squares	F Value	Pr > F
Model	14	13497.9980469	54.70	0.0001
Error	49	863.6962891		
Corrected Total	63	14361.6943359		

R-Square	C.V.	Y1 Mean
0.939861	2.549003	164.707031

Source	DF	Type I SS	F Value	Pr > F
ID	7	13174.7802734	106.78	0.0001-**Significant**
MATERIAL	1	5.4931641	0.31	0.5792
WIDTH	1	229.7119141	13.03	0.0007-**Significant**
MATERIAL*WIDTH	1	23.4619141	1.33	0.2542
MODE	1	26.5869141	1.51	0.2253
MATERIAL*MODE	1	0.2197266	0.01	0.9116
WIDTH*MODE	1	37.1337891	2.11	0.1530
MATERIAL*WIDTH*MODE	1	0.6103516	0.03	0.8531

(b)Dependent Variable: Y2 A1(gs) at f0

Source	DF	Sum of Squares	F Value	Pr > F
Model	14	189.42528108	21.65	0.0001
Error	49	30.62551590		
Corrected Total	63	220.05079699		

R-Square	C.V.	Y2 Mean
0.860825	58.02655	1.36243852

Source	DF	Type I SS	F Value	Pr > F
ID	7	21.51551276	4.92	0.0003
MATERIAL	1	78.72049100	125.95	0.0001-**Significant**
WIDTH	1	48.58096796	77.73	0.0001-**Significant**
MATERIAL*WIDTH	1	34.67478703	55.48	0.0001-**Significant**
MODE	1	1.26684395	2.03	0.1609
MATERIAL*MODE	1	1.81709288	2.91	0.0945
WIDTH*MODE	1	1.18776512	1.90	0.1743
MATERIAL*WIDTH*MODE	1	1.66182038	2.66	0.1094

(c)Dependent Variable: Y3 H(f) at f0

Source	DF	Sum of Squares	F Value	Pr > F
Model	14	0.02360938	1.89	0.0513
Error	49	0.04372142		
Corrected Total	63	0.06733080		

R-Square	C.V.	Y3 Mean
0.350648	2.974573	1.00420984

Source	DF	Type I SS	F Value	Pr > F
ID	7	0.00556114	0.89	0.5213
MATERIAL	1	0.00037631	0.42	0.5191
WIDTH	1	0.00005096	0.06	0.8121
MATERIAL*WIDTH	1	0.00070537	0.79	0.3783
MODE	1	0.00195596	2.19	0.1451
MATERIAL*MODE	1	0.00666856	7.47	0.0087
WIDTH*MODE	1	0.00382867	4.29	0.0436
MATERIAL*WIDTH*MODE	1	0.00446241	5.00	0.0299

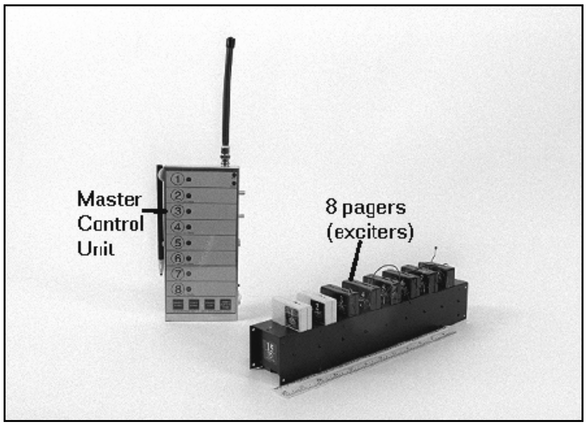

Figure 1 J-TECH 8XT Paging System

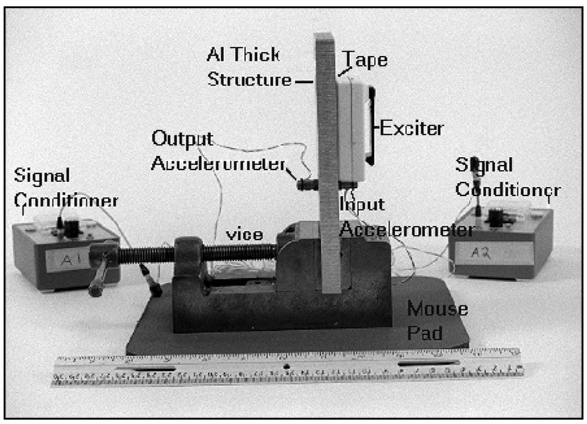

Figure 2 Structural Exciter Prototype

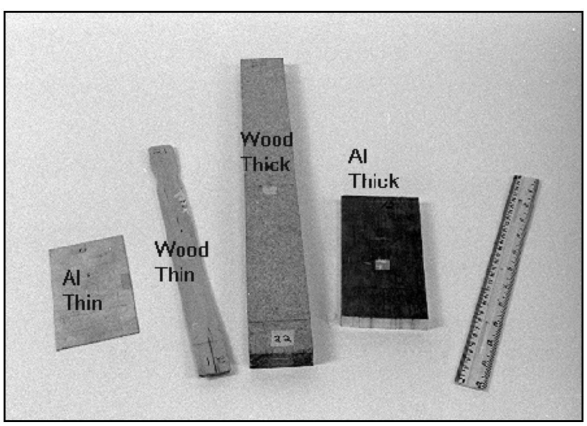

Figure 3 Four Test Structures

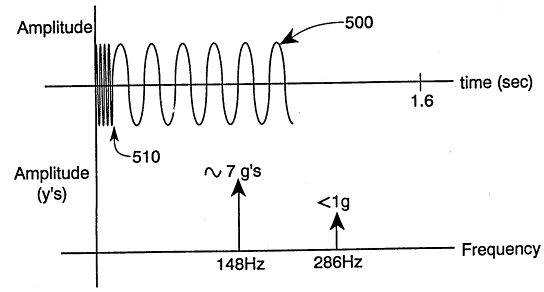

Figure 4 Initial Evaluation

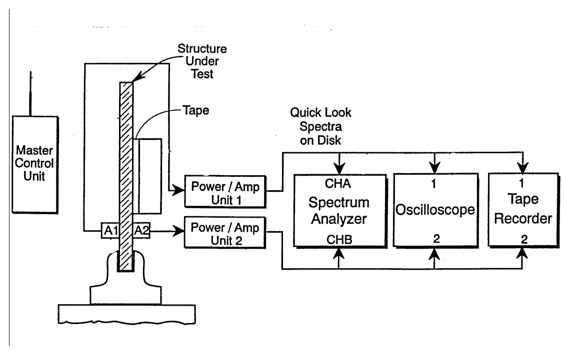

Figure 5 Unattached Structure Exciter Prototype

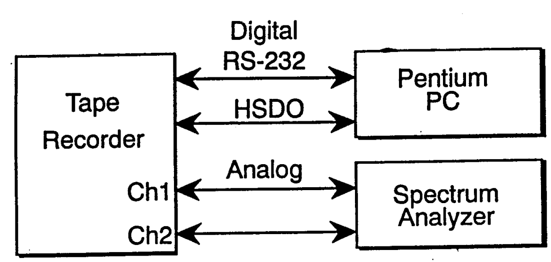

Figure 6 Play Back Block Diagram

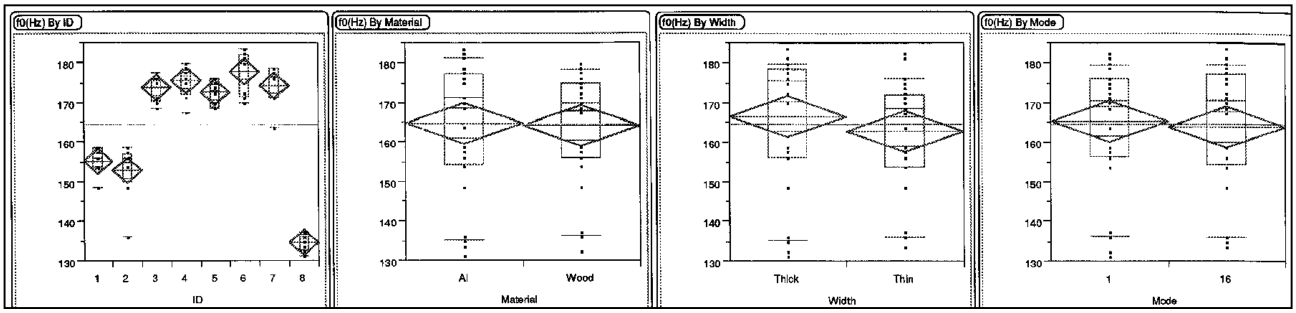

Figure 7 Frequency Mean Diamonds and Quantile Boxes by ID, Material, Width and Mode

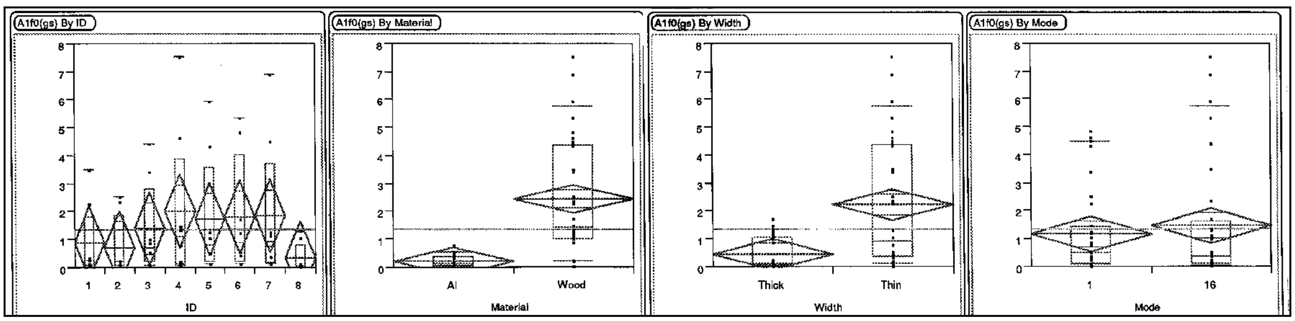

Figure 8 Vibration Amplitude Mean Diamonds and Quantile Boxes by ID, Material, Width and Mode

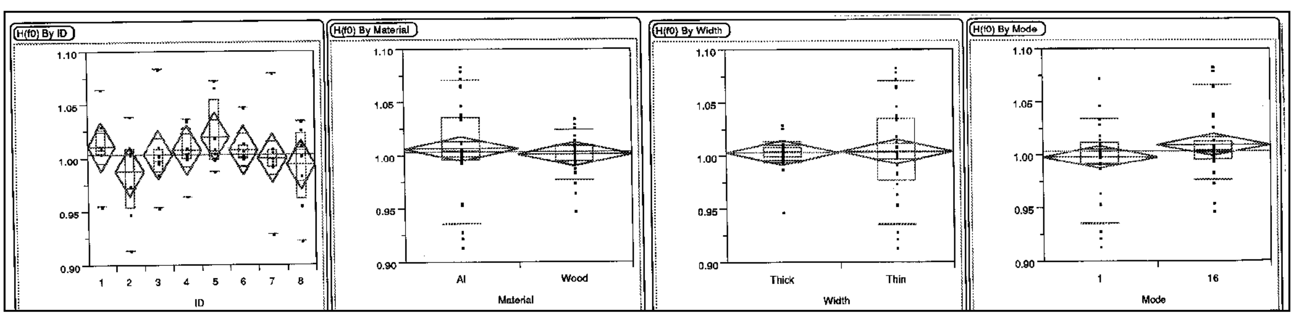

Figure 9 Transfer Function Mean diamonds and Quantile Boxes by ID, Material, Width and Mode